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Memo

DATE: *October 7, 2005*

TO: RHIC E-Coolers

FROM: *Ady Hershcovitch*

SUBJECT: **Minutes of the October 7, 2005 Meeting**

Present: Ilan Ben-Zvi, Alexei Fedotov, Harald Hahn, Lee Hammons, Ady Hershcovitch, Dmitry Kayran, William Mackay, Derek Lowenstein, Thomas Roser, Alexander Smirnov (JINR Dubna, Russia), Gang Wang (SUNY Stony Brook).

Topics discussed: Electron Cooling Computations and Simulations with Comparison to Experiments, Diamond Cathode.

Electron Cooling Computations and Simulations with Comparison to Experiments: most of the meeting consisted of a presentation given by Alexander Smirnov of JINR Dubna, Russia, who had just spent three weeks at BNL. In the presentation, he described the BETACOOL code and its application to simulate non-magnetized cooling of antiprotons by an electron beam that was performed at the FNAL Recycler ring. The code simulates long-term (compared to the ion revolution period) processes that lead to variations in the ion distribution function in six dimensional phase space. The simulation is applicable to stable ion beams that can be treated with linear approximation. Below is Smirnov's presentation.

Simulations were compared to the first ever non-magnetized cooling that was performed on July 15th, 2005 on the FNAL Recycler ring. In that experiment non-magnetized electron beam cooling of antiprotons was performed. The third slide of the presentation clearly indicates the shrinkage of the antiproton momentum spread (in red) after electron beam cooling from the original spread (in blue). Over all the simulations showed good agreement with the experiments. Friction force value strongly depends on the parameters of electron cooler; but more experimental results are needed for accurate BETACOOL benchmarking. Asymptotic expression for the cooling force cooling force worked well for the FNAL parameters, but for RHIC parameters the friction force requires numerical integration.

In answer to Thomas, Alexei said that BNL involvement in FNAL experiments is planned for November when Anatoly Sidorin (JINR Dubna Russia) is due to come to BNL.

Diamond Cathode: the meeting ended with Ilan showing the latest diamond cathode results, which are encouraging. Due to the preliminary nature of the results, details will be furnished at a later date.

Comparison of longitudinal non-magnetized friction force measurement at FNAL Recycler with simulations using the BETACOOL code

A.Fedotov, A.Smirnov

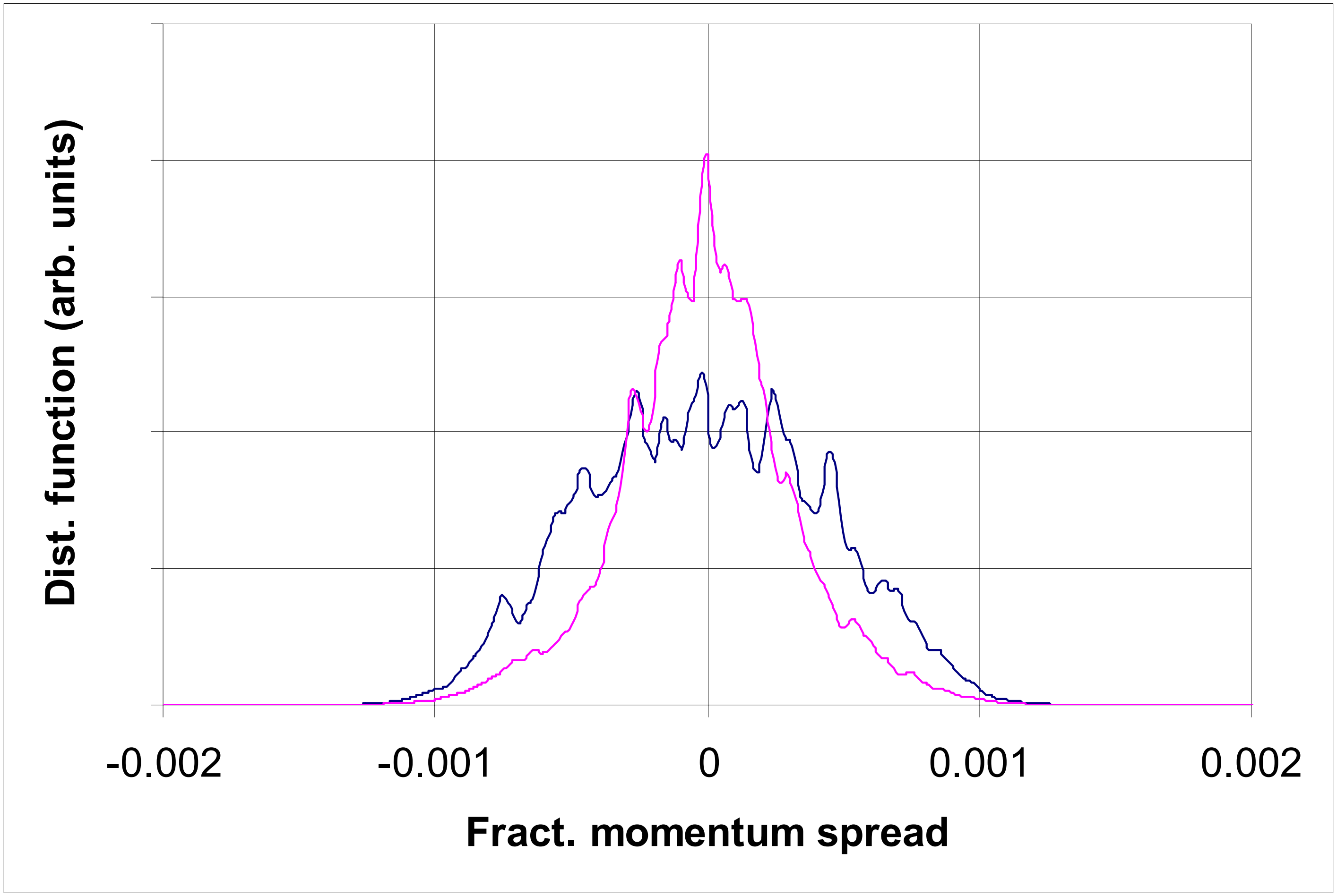
BNL, 10/07/2005

General goal of BETACOOL code:
- Simulation of long-term processes
  (long - in comparison with the ion revolution period)
  leading to variation of the ion distribution function
  in 6 dimensional phase space.
- The ion beam motion inside a storage ring is supposed
  to be stable and is treated in linear approximation.

New advantages in the frame of collaboration with BNL:
- Model Beam algorithm with modeling particles
- Improved models of Electron cooling description
- Significant improvement of various algorithms: Electron cooling, Intrabeam scattering, Collision point, etc.
- Version under LINUX, implementation into UAL

First non-magnetized e-cooling demonstration – 07/15/05

Pbar beam: 63.5e10, Barrier-bucket bunched, Bunch length 1.7-us
Tr. emittance (95%,n) kept at 4-pi mm-mrad
Electron beam current: 200 mA, Traces are 15 min apart

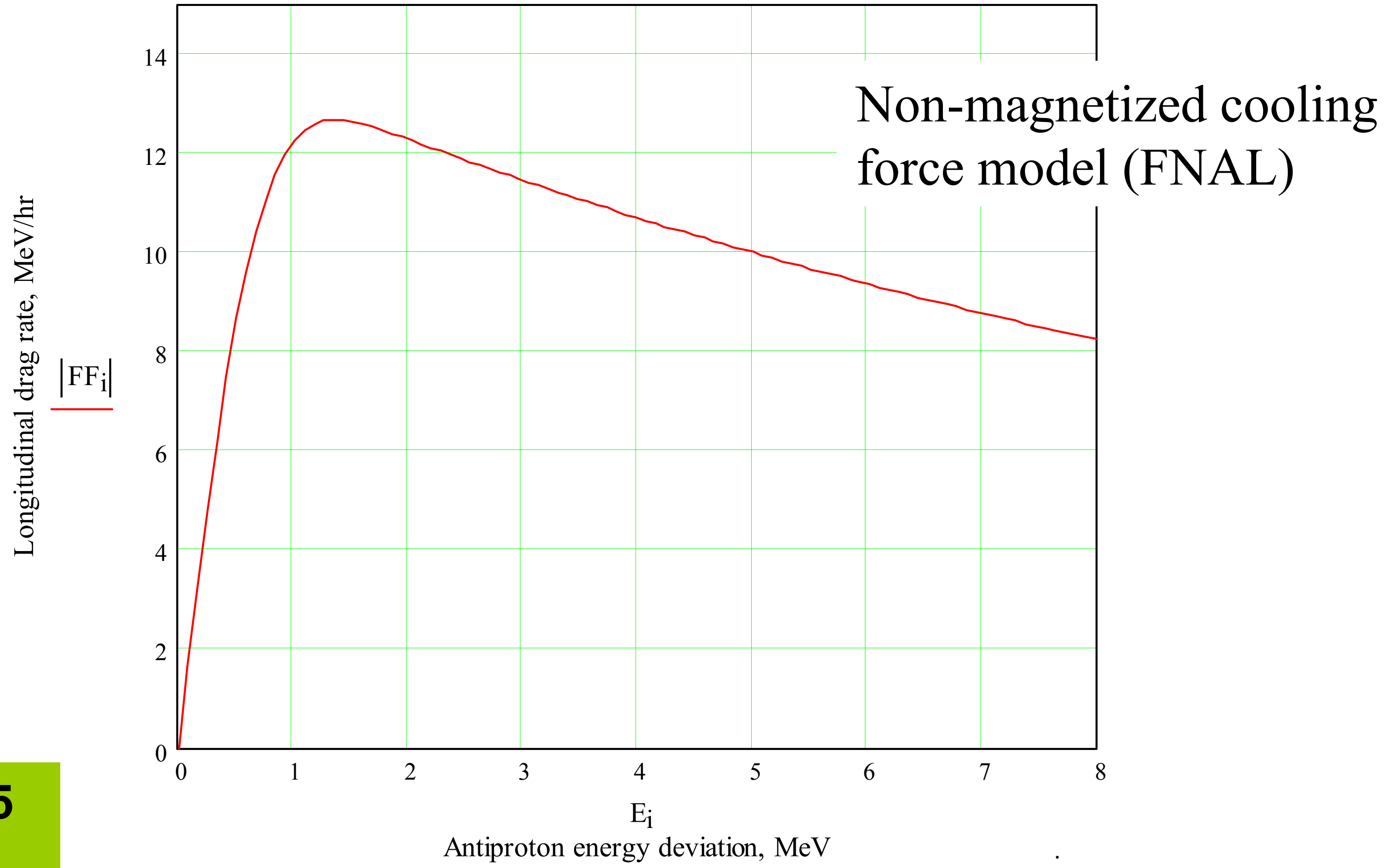


Electron beam parameters

• Electron kinetic energy	4.34 MeV
• Uncertainty in electron beam energy 0.3 %	
• Energy ripple	$\leq 10^{-4}$
• Beam current (max)	0.5 A DC
• Duty factor (averaged over 8 h)	95 %
• Electron angles in the cooling section (averaged over time, beam cross section, and cooling section length), rms	$\leq$ 0.2 mrad

Electron cooling drag rate

- For an antiproton with zero transverse velocity, electron beam: 200 mA, 3-mm radius, 300 eV rms energy spread and 0.2 mrad angular spread



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Models used in BETACOOL

Numerical

$$F_{\parallel} = -\frac{4\pi Z^2 e^4 n_e}{m \cdot Int} \int_0^{3\Delta_\perp} \int_{-3\Delta_\parallel}^{3\Delta_\parallel} \int_0^{\pi} \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{(V_\parallel - v_\parallel)\exp\left(-\frac{v_\perp^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right)}{\left((V_\parallel - v_\parallel)^2 + (V_\perp - v_\perp \cos\varphi)^2 + v_\perp^2 \sin^2\varphi\right)^{3/2}} v_\perp d\varphi dv_\parallel dv_\perp$$

Asymptotic (Meshkov)

$(v_i << \Delta_{||})$

$$F_{\parallel} = -\frac{4\pi Z^2 e^4 n_e L(v_i)}{m} \frac{v_\parallel}{\Delta_\parallel \Delta_\perp^2}$$

$(\Delta_{||} << v_i << \Delta_\perp)$

$$F_{\parallel} = -\frac{4\pi Z^2 e^4 n_e}{m} L(v_i) \frac{v_\parallel}{|v_\parallel| \Delta_\perp^2}$$

Asymptotic (Derbenev)

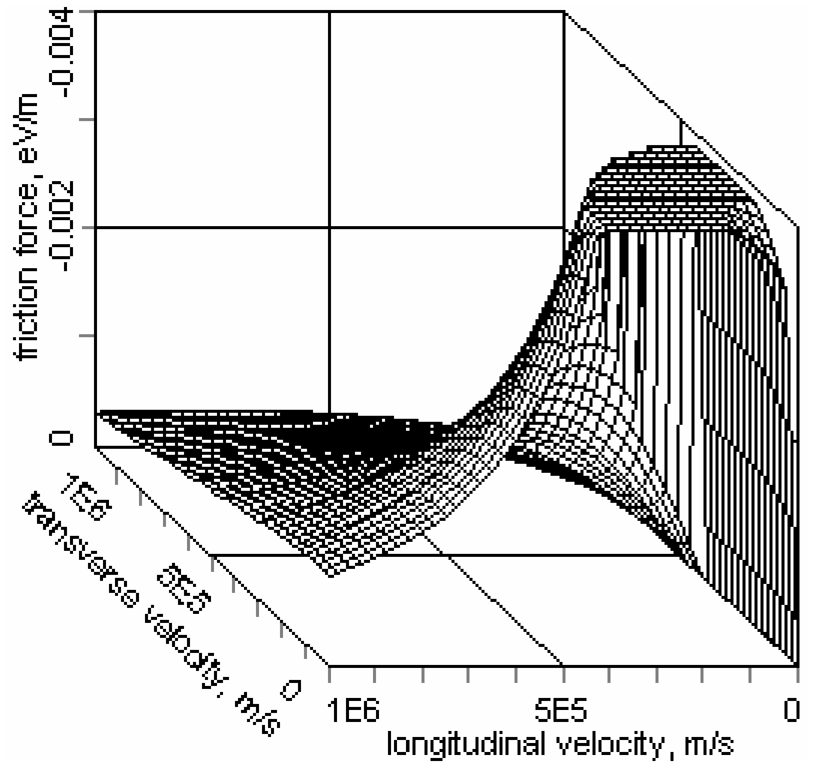
$(v_{||} << \Delta_{||})$

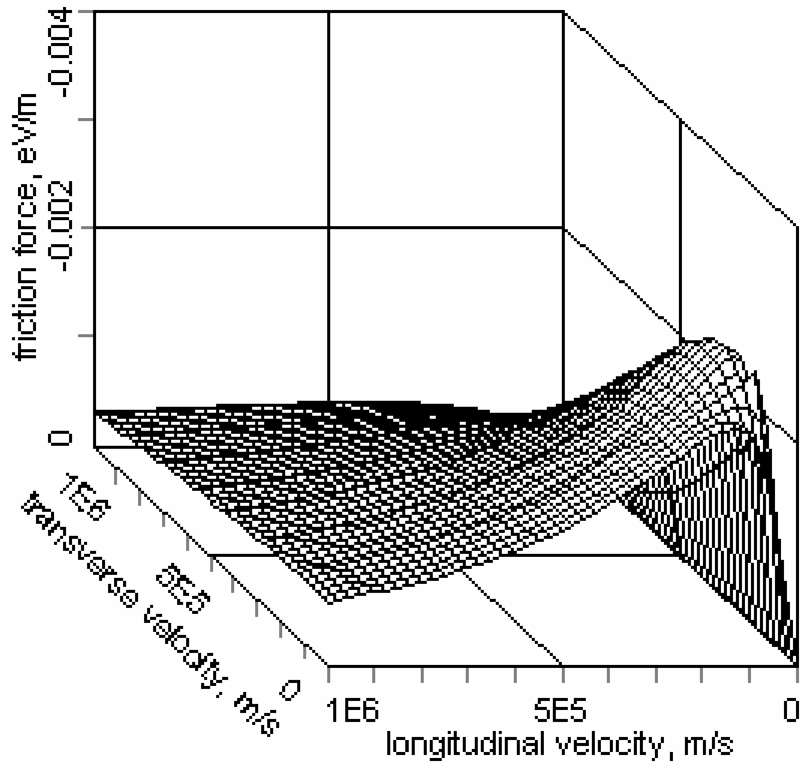
$$F_{\parallel} = -\frac{4\pi Z^2 e^4 n_e L(v_\parallel)}{m} \frac{v_\parallel}{\Delta_\parallel \Delta_\perp^2} \sqrt{\frac{2}{\pi}}$$

$(\Delta_{||} << v_{||} << \Delta_\perp)$

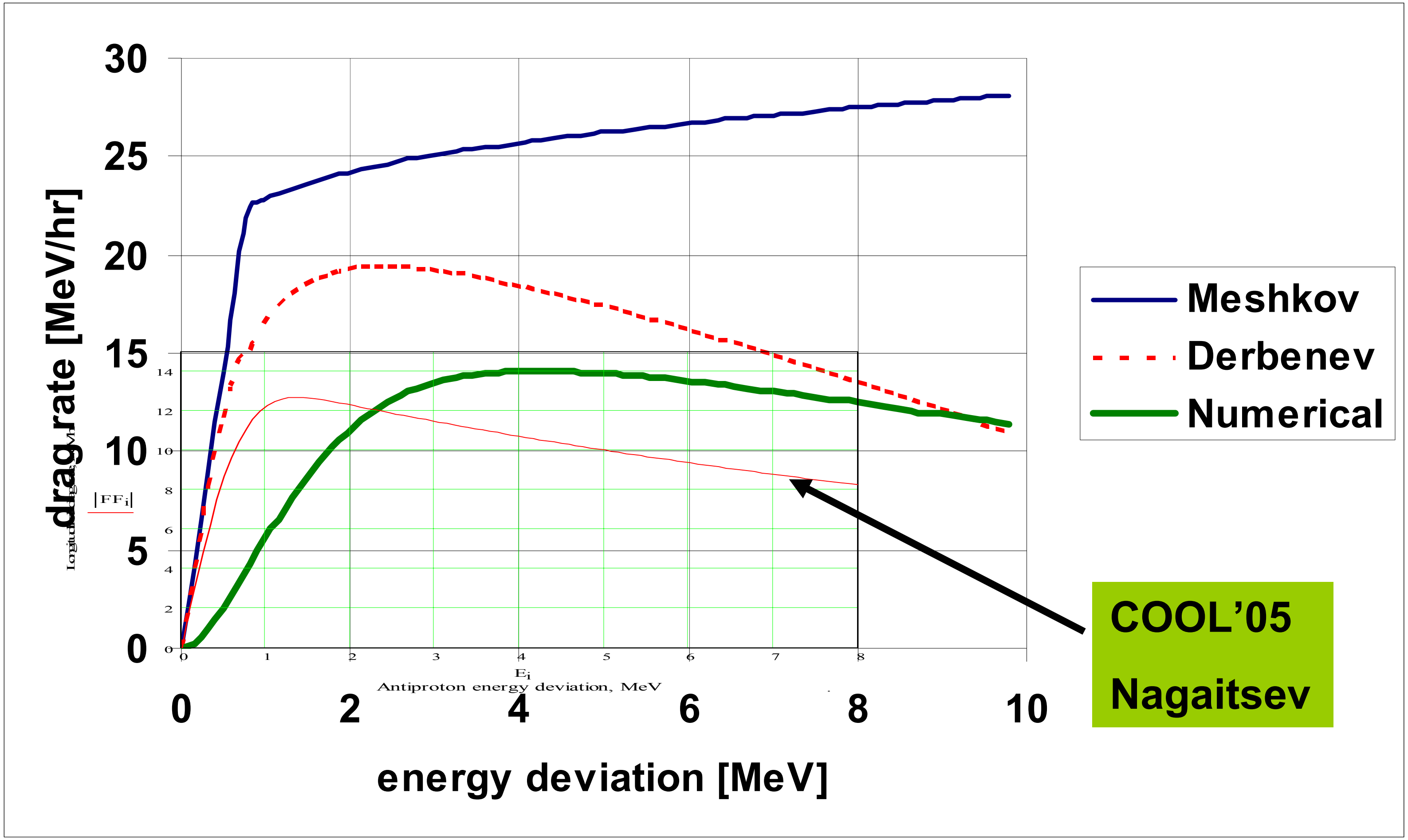
$$F_{\parallel} = -\frac{4\pi Z^2 e^4 n_e}{m} \left[L(v_\parallel) \frac{v_\parallel}{|v_\parallel| \Delta_\perp^2} - \sqrt{\frac{\pi}{2}} L(\Delta_\perp) \frac{v_\parallel}{\Delta_\perp^3} \right]$$

Longitudinal friction force
(BETACOOL - asymptotic and numerical)

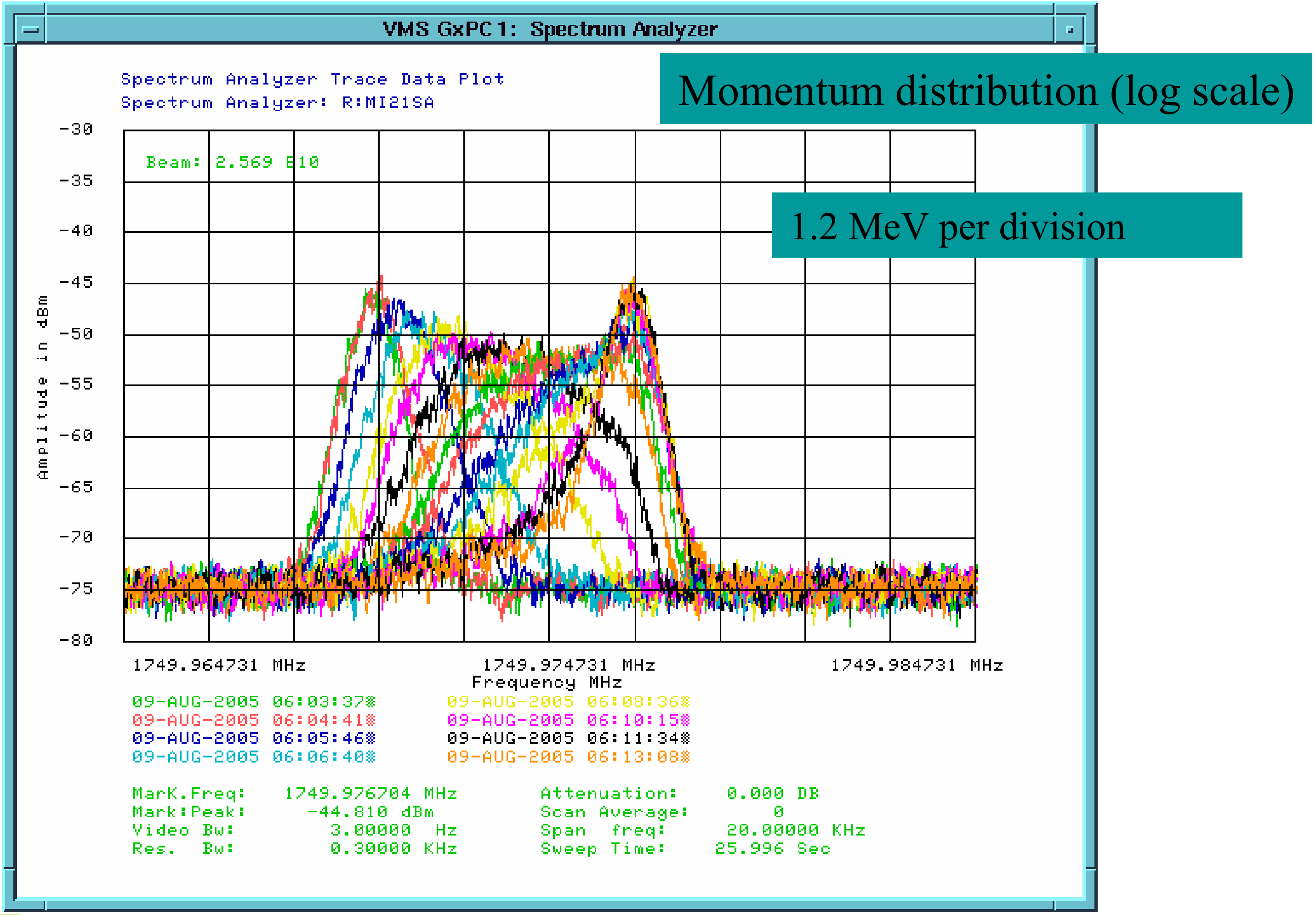




Longitudinal drag rate
(BETACOOL simulation for $v_{i\perp}$=0)

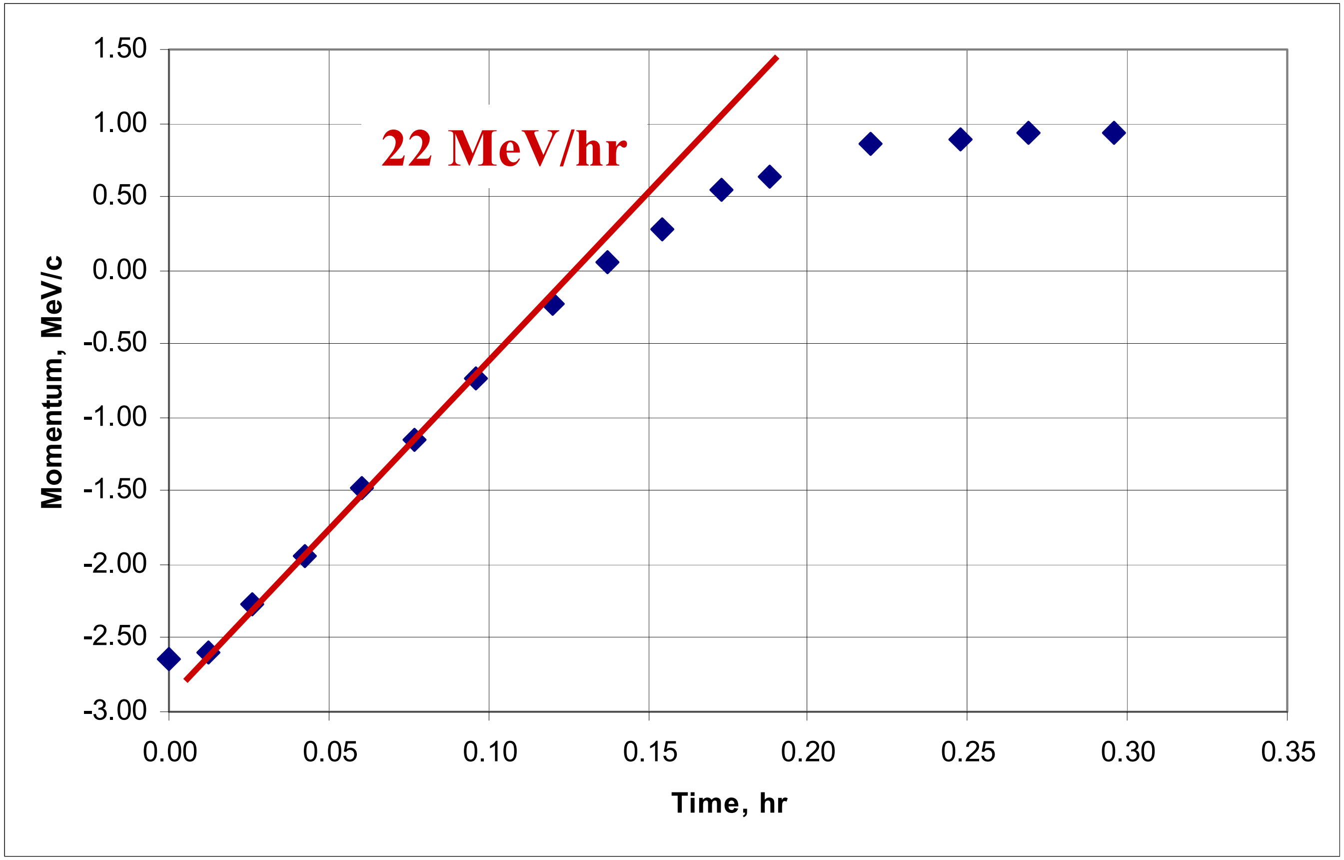


Drag force measurements: electron energy jump by +2 keV



Beam emittance was measured by Schottky: 1.5 µm (n, 95%).
In the cooling section this corresponds to a 0.9 mm radius (rms), electron current 200 mA

Drag force – voltage jump +2 kV



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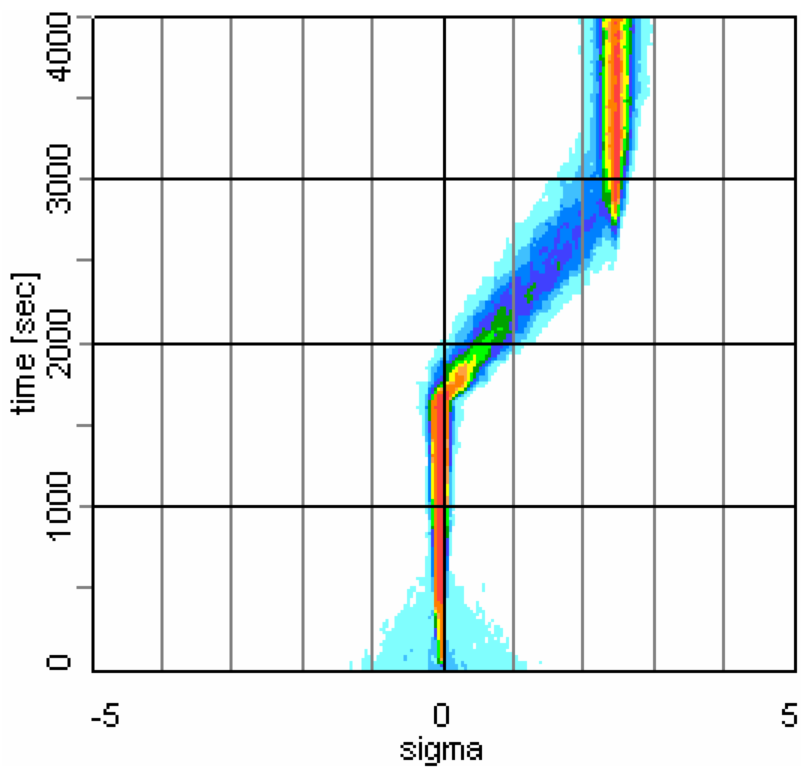
Modeling in BETACOOL

Drag rate measurements were directly modeled using the BETACOOL code:

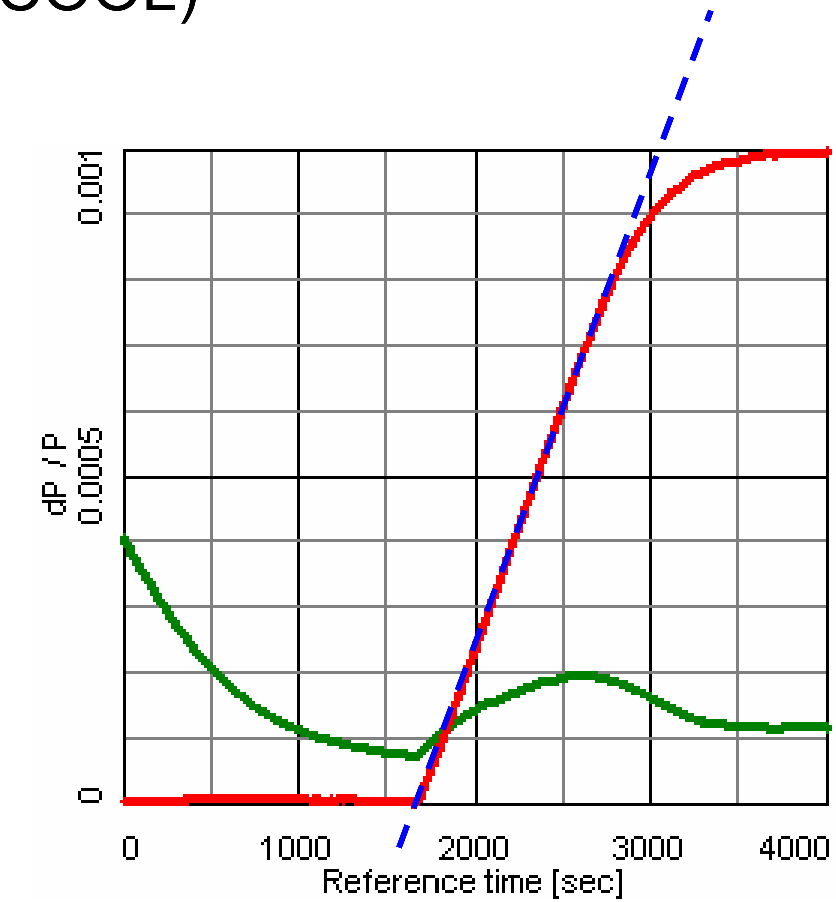
Steps:

1. Pbar distribution was cooled first
2. Electron energy was changed
3. Pbars are dragged towards new energy
4. Rate of the drag is measured
5. This was repeated for different electron energy jumps to construct a drag-rate curve.

Example for the shift of electron energy +4.3 kV (BETACOOL)



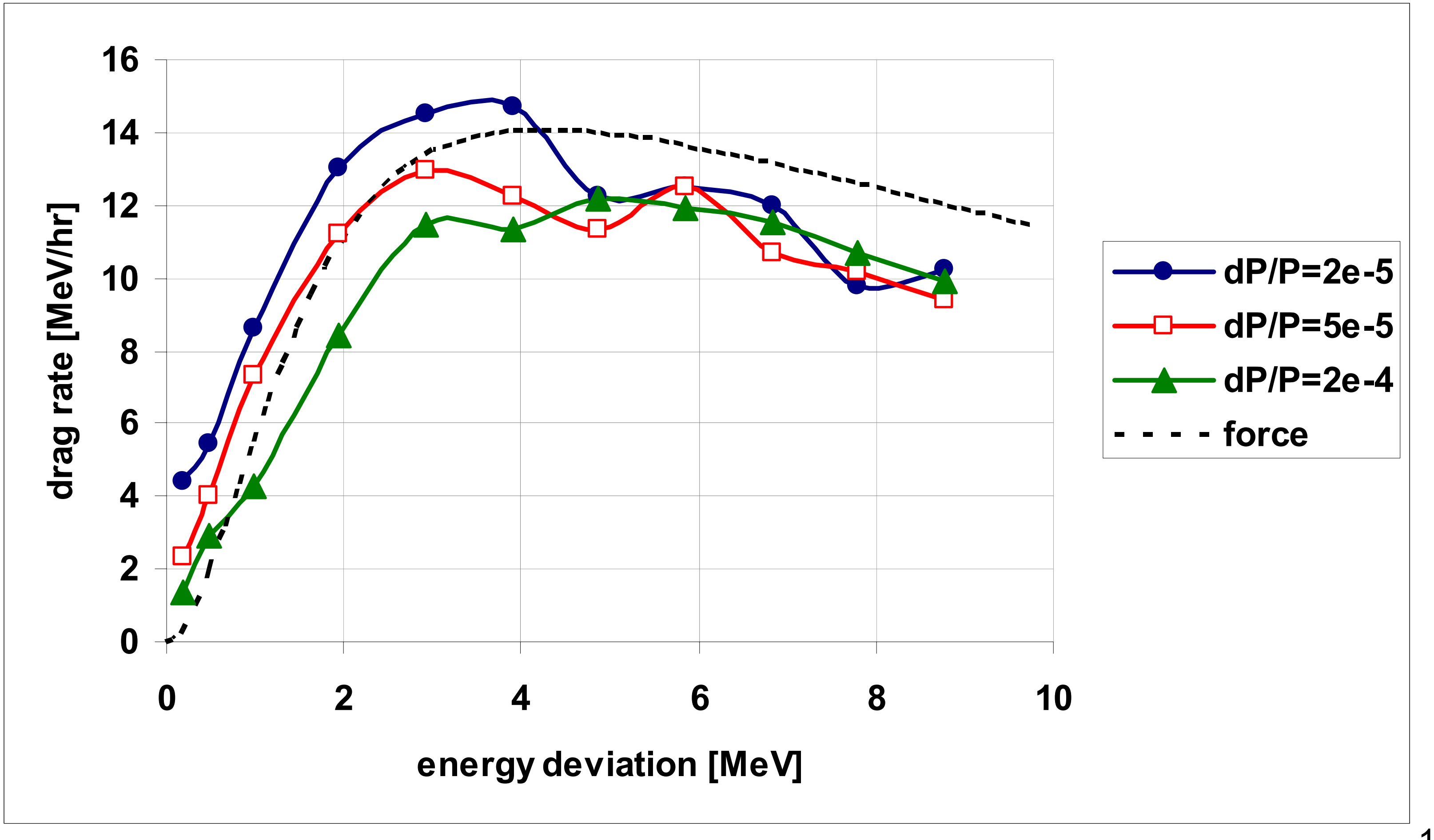
Rms momentum spread in time



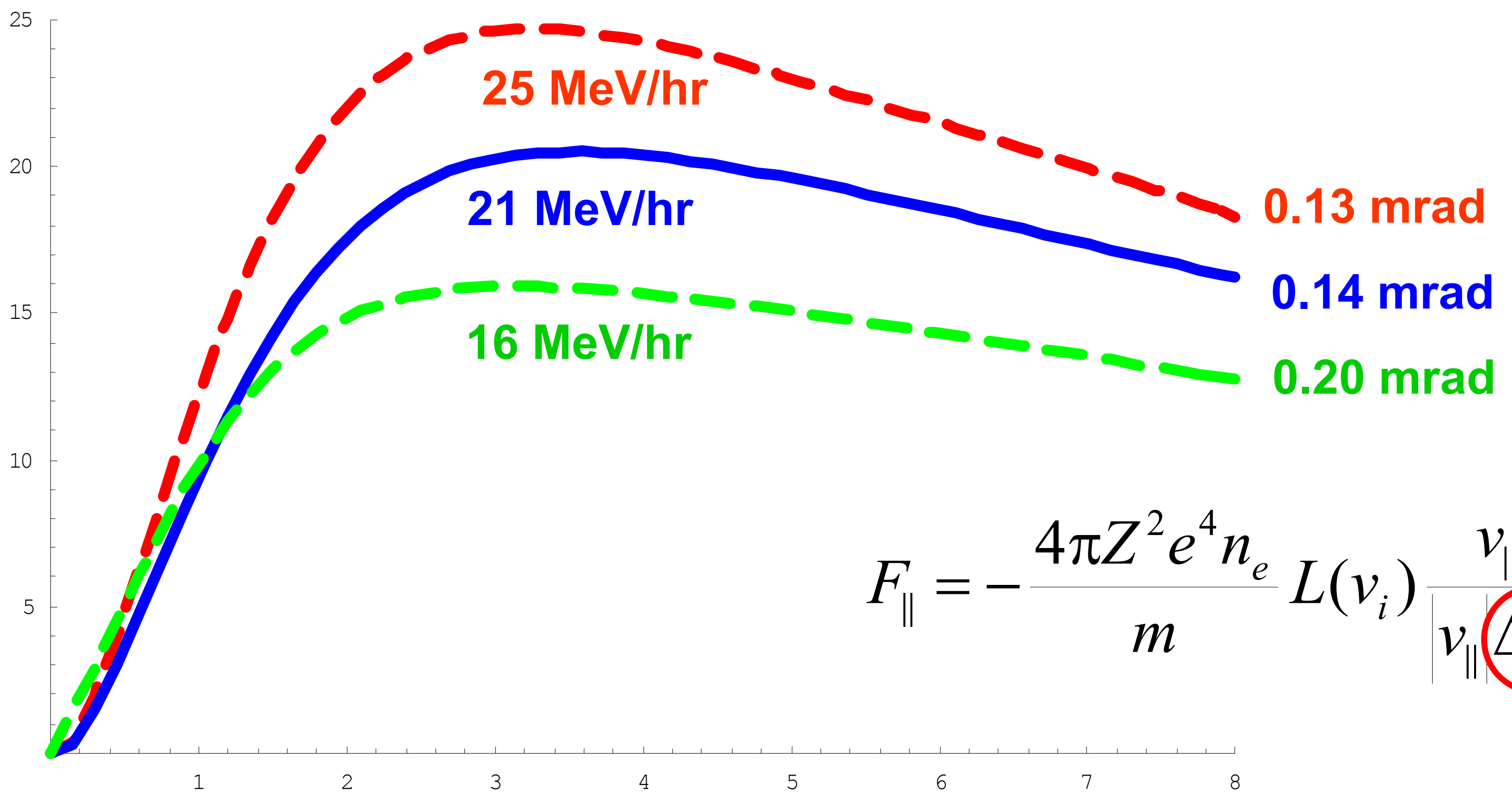
Rms momentum spread and momentum deviation in time

Friction force for different initial rms momentum spread

(BETACOOL - numerical calculation of friction force)



BETACOOL- numerical friction force – dependence on transverse angles (velocities) of electrons



$$F_{\parallel} = -\frac{4\pi Z^2 e^4 n_e}{m} L(v_i) \frac{v_{\parallel}}{|v_{\parallel}| \Delta_{\perp}^2}$$

Comparison of Recycler experiments and simulation:

- Results of numerical simulation of non-magnetized friction force are in good agreement with experiments
- Approximation ($v_{e\perp} >> v_{e||}$) is sufficient for FNAL parameters.
- For RHIC - numerical integration is needed.
- Friction force value strongly depends on the parameters of electron cooler. More experimental results is needed for accurate benchmarking of the BETACOOL code

Future plans of BETACOOL development:

- Implementation of new models: Stochastic cooling, Optical Stochastic Cooling, Direct modeling of experiments on bunched ion beam (with RF phase)
- Improvement of many other models.
- Simulation of colliding experiments with different spices of ions (2 storage rings – 2 ion beams)